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Tracking Performance in LHCb

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Abstract. The tracking system of the LHCb detector has been re-optimised to reduce the amount of material which particles traverse. The different subcomponents involved in tracking are described. The track reconstruction algorithms are shown to have a good efficiency for finding tracks with the re-optimised setup. The tracking system is capable of providing the excellent spatial and momentum resolutions which are required for the challenging physics program of LHCb.

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1 Introduction

The aim of LHCb [1] is to study CP violation and rare decays in the B sector. LHCb is designed as a single arm forward spectrometer, which will be located at the LHC. It aims to collect a high statistics sample of B decays. One of the challenges in its environment of high track density is to have a sufficiently fast track reconstruction, while keeping a high efficiency.

2 The tracking system

Recently the LHCb setup has been re-optimised [2, 3]. The current setup of LHCb is shown in figure 1. One of the main changes is that in the tracking system several stations are removed. The tracking system can be divided globally into three sub-systems. First, a silicon Vertex Locator [4] (VELO) is built around the interaction point. Second, the Trigger Tracker (TT), consisting of two silicon stations, is placed after the first Cherenkov detector (RICH1) and just in front of the magnet. Finally, after the magnet there are three tracking stations: T1, T2 and T3. These stations contain two different detector technologies. The inner part, called the Inner Tracker [5] (IT), is close to the beam pipe and is a silicon strip detector. The Outer Tracker [6] (OT) is placed around the Inner Tracker and is made out of straw drift chambers. The combination of IT and TT is also referred to as Silicon Tracker.

2.1 The Vertex Locator

Each of the 21 stations in the VELO has an r- and a ϕ-measuring layer. The sensors are 220 μm thick and the pitch between the strips ranges from 37 μm to 103 μm, depending on the distance to the beam. The sensitive area of the

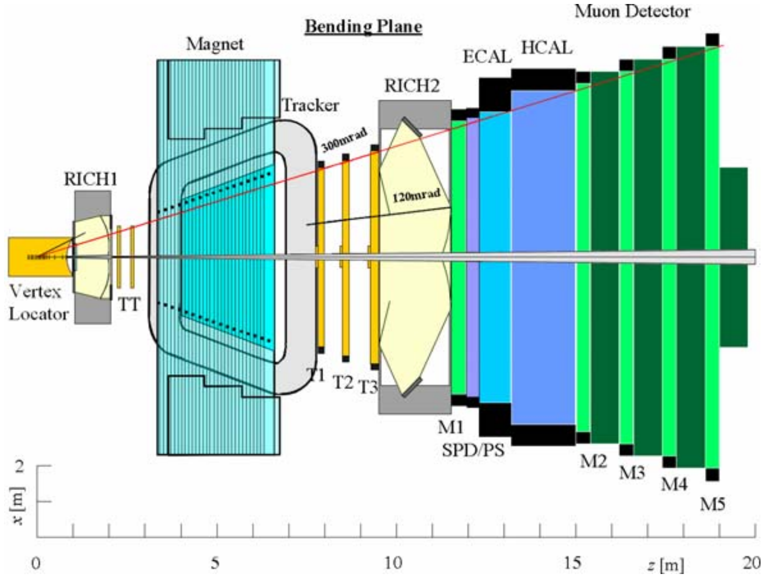

Fig. 1. The re-optimised LHCb detector setup, shown in the bending plane.

sensors starts at only 8 mm from the beam axis. This allows for a very accurate measurement of the impact parameter (IP) of the tracks with respect to the primary vertex. This is required for determining the proper decay time of the B mesons, especially in the case of the fast-oscillating B_s mesons. The impact parameter resolution of reconstructed tracks is plotted in figure 2 as a function of the inverse of the transverse momentum, p_T. The resolution can be parametrised as:

$$\sigma_{IP} = 17\mu\mathrm{m} + \frac{32\mu\mathrm{m}}{\mathrm{p_T}} \tag{1}$$

where p_T is in units of GeV/c. For B decay tracks the resolution ranges between 20 and 40 μm.

2.2 The Silicon Tracker

The Silicon Tracker consists of the Trigger Tracker and the Inner Tracker.

Information from the Trigger Tracker is used in the Level-1 trigger. The fringe magnetic field between the VELO and the two TT stations allows the trigger to obtain a sufficient momentum estimate for the Level-1 VELO tracks. The trigger selects those tracks having a large p_T and a high impact parameter [7]. Since high momentum tracks have a small deflection at TT, silicon is the chosen technology. The distance between the two TT stations is 30 cm. Each TT station has two silicon layers which are approximately 1.4 m wide and 1.2 m high. The silicon sensors are about 500 μm thick and have a 198 μm readout pitch.

The Inner Tracker covers the region of highest occupancy in the T-stations. An IT station has four boxes of silicon sensors. These four boxes are placed

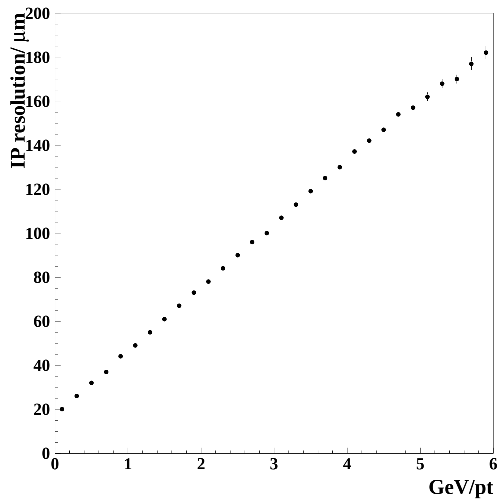

Fig. 2. The impact parameter resolution of the reconstructed tracks with respect to the primary vertex versus $1/p_T$.

around the beam pipe in a cross-shape. An IT station is about 125 cm wide and 40 cm high. The cross-shape has been chosen as the optimal shape of the Inner Tracker. This was done to limit the occupancy in the Outer Tracker. Figure 3 shows that the OT occupancy is highest towards the beam pipe. The cross-shape boundary between the Inner and Outer Tracker keeps the occupancy below 7% in the hottest Outer Tracker regions. Note that these occupancies are averaged over many events and that there is a large tail of events with large hit and track densities. The silicon sensors are 320 μm thick and also have a 198 μm pitch, resulting in a resolution of 45 μm. The strips have a vertical orientation to have the best resolution in the bending plane. The four layers in each station are configured at $0°, +5°, -5°$ and $0°$ with respect to the vertical axis. The same configuration is used in the OT and for the four layers in the TT.

2.3 The Outer Tracker

In the stations T1-T3, the Outer Tracker covers the region outside the acceptance of the Inner Tracker. The straws are 5 mm in diameter. In the 4.7 m long modules the wires are split in the middle, and therefore they are read-out at the top and bottom. To guarantee a signal collection within 50 ns, corresponding to 2 LHC beam crossings, a fast drift gas ($Ar(75)/CF_4(15)/CO_2(10)$) is chosen. The spatial resolution obtained in test beam with this gas is 200 μm.

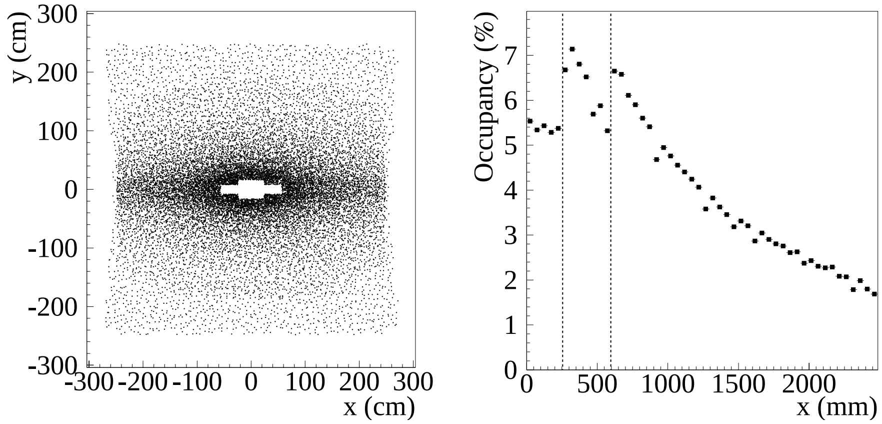

Fig. 3. On the left the distribution of hits is shown in y versus x. The high density of hits around the beam pipe is clearly visible. On the right the OT occupancy versus x is plotted. The dashed lines are the vertical boundaries between the IT and OT.

3 Track finding and fitting

The intense hadronic environment of the LHC gives a high density of hits and tracks in the experiment. This makes track finding in LHCb a hard and time-consuming job. Apart from the off-line reconstruction, B-candidate tracks must also be reconstructed at trigger level. In both trigger and off-line reconstruction the CPU-consumption must be low. The track finding efficiency must be as high as possible. This is particularly important for many-prong B decays, where the total efficiency is the product of the single track efficiencies. In addition, any material in the acceptance before the calorimeters must be of low radiation- and interaction length, otherwise there will be too many secondary particles and too many losses due to hadronic interactions of particles with the material. These requirements put stringent constraints on the lay-out of the LHCb detector.

The tracking setup of LHCb makes the development of different specialised track finding algorithms necessary. The current track pattern recognition algorithms are summarised below.

First of all, in the VELO the magnetic field is sufficiently low that tracks can be considered as straight lines here. The algorithm [8] starts with making three-dimensional space points by combining r and ϕ clusters. Then triplets of space-points are searched, allowing for detector inefficiencies. Extrapolating towards the interaction point other clusters are added, again taking into account possible inefficiencies. These VELO tracks are used for reconstructing the primary vertex and as input to other track finding algorithms.

Another algorithm, called forward tracking, starts with these VELO tracks and tries to find continuations in the TT and T stations. The idea [9] is that for a given VELO track and a single hit in T1, T2 or T3, the trajectory of the track through the experiment is determined. In this algorithm the trajectory is parametrised by a second (in y) and third order (in x) polynomial. A fast histogramming method selects the best trajectories and adds the hits to the track candidate. Finally, a likelihood method is applied to confirm the correct tracks and reject the ghosts. The hits used by the forward tracks are discarded for use in the remaining track search algorithms.

Since there is only a small fringe field in the T stations, this region is also well-suited for finding tracks. The track seeding [10] is a stand-alone algorithm which searches for tracks in the T1-T3 stations. It starts looking for track candidates in the xz plane by considering only the hits in the $0°$ layers. Later, the stereo-hits are added to confirm the 2D track candidates. Also here a likelihood method is used to reject ghosts.

A matching algorithm [11] attempts to combine these seed tracks with VELO tracks. First the momentum of the seed tracks is estimated. Knowing the slopes and position after the magnet, and assuming that the seed track originated from a nominal vertex position, a momentum resolution $\delta p/p \sim 1\%$ can be obtained. This momentum is used to extrapolate the seed track through the magnetic field towards the VELO. There, a χ^2 criterion is used to select the correct match with the VELO tracks.

Tracks which extend from the VELO all the way up to T3, e.g. forward and matched tracks are referred to as *long tracks*. These are the tracks with the best momentum resolution. The B decay products are typically reconstructed as long tracks and therefore these tracks are used in most physics analyses.

Some tracks originating in the VELO do not make it to the T stations, since their momentum is too low and they get bend out of the acceptance by the magnetic field. These tracks are named VELO-to-TT tracks, or VTT tracks. A dedicated algorithm searches for these tracks. It extrapolates VELO tracks, which are not part of a long track, as straight lines in the yz-plane to the TT stations. Then, for each hit which is compatible with this extrapolation, a momentum is estimated. When at least three hits in the four layers have a similar momentum, the whole track is re-fitted with a Kalman filter [12]. The candidate track is accepted when it satisfies $\chi^2/\mathrm{NDF} < 5$.

There are also tracks which do not leave (enough) hits in the VELO, but do have hits in TT and T1-T3 (e.g. pions originating from a $\mathrm{K_S^0}$ decay). These are the so-called T-to-TT tracks or TTT tracks. The algorithm [13] which looks for these tracks loops over the seed tracks and estimates the momentum in the same way as the matching algorithm. Then these seed tracks can be extrapolated to the TT stations and hits are searched based on a Kalman filter approach.

Finally, all tracks are re-fitted with a Kalman filter. Using the amount of traversed material and the momentum of the track, the multiple scattering and energy loss are properly taken into account.

4 Tracking performance

An excellent tracking performance is an important input for the physics analysis [14]. A high tracking efficiency is needed. Good spatial and momentum

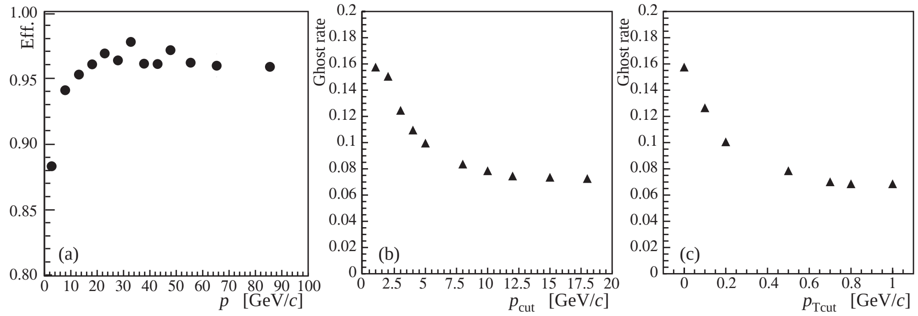

Fig. 4. Tracking efficiency for long tracks as a function of momentum, p (a). Ghost rate for long tracks with a reconstructed momentum greater than $p_{\rm cut}$ (b) and transverse momentum greater than $p_{\rm T,cut}$ (c).

resolutions are required for finding the B decay vertex and resolving B_s oscillations.

On average 74 tracks are reconstructed per event. This number is composed of 23 VELO tracks, 27 long tracks, 4 seed tracks, 10 VTT tracks and 10 TTT tracks. The average momentum of the long tracks is 13 GeV and they have about 37 measurements, consisting of VELO, TT, IT and OT measurements.

The efficiencies are normalised to a sample of "reconstructible" particles:

- for VELO tracks the particles must leave at least 3 r and 3 ϕ hits,
- for seed tracks, in each station of T1-T3, the particles must have at least 1 hit in a 0°-layer and 1 hit in a stereo-layer (+5° or −5°).

For the long tracks the Monte Carlo particles must be reconstructible as VELO and seed track; for the VTT tracks they must be reconstructible VELO as track and have at least 3 hits in TT; and for the TTT tracks the particles must be reconstructible as seed track and have at least 1 hit in TT. In order to count as successfully reconstructed track, at least 70% of the hits must come from a single MC particle. The long tracks must be successfully reconstructed in the VELO and T1-T3. For the VTT tracks and TTT tracks the requirement is that they are successfully reconstructed in the VELO and T1-T3 respectively, and have, in addition, at least 1 correct hit in TT.

It is found that the average efficiency for the long tracks is 92%. The average ghost rate is 16%, with large event-to-event fluctuations. In figure 4 it can be seen that the efficiency rises with the momentum. For $p > 5$ GeV the efficiency is more than 95%. Also, the ghost rate drops when the low momentum tracks are cut away. Since B decay tracks typically have $p_{\rm T} > 0.5$ GeV the corresponding ghost rate is only 8%. The efficiency for these B tracks is $\sim$ 95%. The VTT tracks are found with an efficiency of about 75% and a ghost rate of about 12%.

The TTT tracks are mainly used for enhancing the efficiency for finding charged pions from $\rm K^0_S$ decays. Due to their long decay lengths, many of these pions will not leave (enough) hits in the VELO. Only about a quarter of the

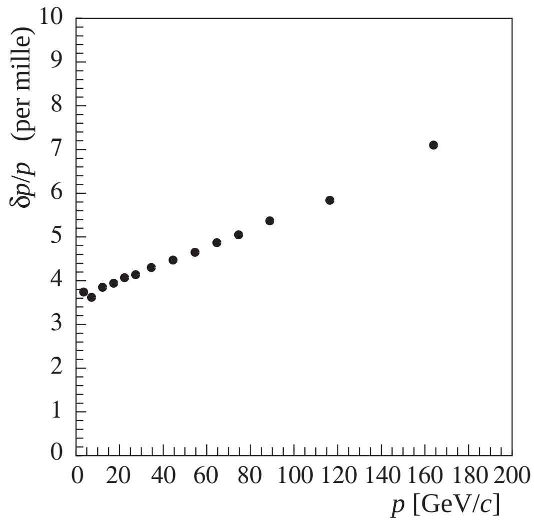

Fig. 5. Momentum resolution of long tracks at the vertex as a function of momentum. The resolution is the result of a single Gaussian fit in each bin.

K^0_S decays will be reconstructible in the VELO. These can be reconstructed as long and VTT tracks. Half of the K^0_S's decay outside the VELO, but before the TT. These are reconstructible as TTT tracks. The efficiency to find the two pions from this decay is 54%, corresponding to a single track efficiency of about 74%.

Several tests were done to check the robustness of the tracking against worse conditions. One example is the efficiency as a function of the number of primary interactions in a single event. Although the luminosity can always be tuned to have the maximum number of single interactions and the Level-0 trigger will reject many multiple interaction events, still it is re-assuring that even for 4 simultaneous interactions the track reconstruction efficiency drops only 3%. The ghost rate rises with the number of interactions due to the increase in combinatorics, but was found to be less than 40% even at 4 interactions. Additional tests assuming lower hit efficiencies, decreased hit resolutions and more noise hits also showed a robust tracking performance.

LHCb provides an excellent momentum estimate at the vertex. The momentum from the track fit for long tracks has a core resolution of 0.35% (tail fraction is 0.1 with $\sigma = 1.0\%$). The momentum resolution depends on the momentum as is shown in figure 5. For TTT tracks the momentum resolution is 0.43%. This is only slightly worse than for long tracks, since they still traverse through most of the magnetic field. The VTT tracks have their last measurement at the second TT station and therefore they see only the field up to this point. Their momentum is estimated with a precision of $\delta p/p \sim 20\%$.

The reconstructed tracks are an important input to the physics sensitivity studies. An example is the decay channel $B_s \to {D_s}^{\mp}(\to KK\pi)\pi^{\pm}$. In this channel the four B daughters are all reconstructed as long tracks. The total tracking efficiency is $84.6 \pm 0.5\%$, which corresponds to a single track efficiency of 95.6%. The mass of the B_s in this decay is measured with a resolution of 12.6 ± 0.6 MeV and the vertex with a resolution of 168 ± 15 μm. Finally, the proper time of the B_s decay is measured with $\sigma_\tau = 42 \pm 5$ fs, sufficient to resolve the B_s oscillations up to $\Delta m_s = 48$ ps^{-1}.

5 Conclusions

The tracking system in LHCb is robust and provides the high spatial and momentum resolutions required in the physics analyses. In addition, the tracking efficiency for finding B mesons, including K^0_S's is sufficient to give the high statistics of B decays needed for the challenging physics program.

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